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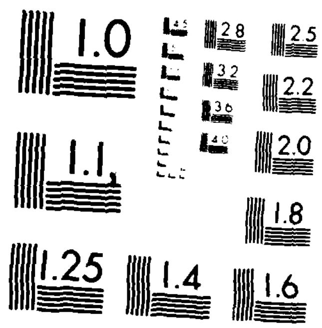

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PROSPECTS FOR LOW-COST ADVANCED COMPUTER-BASED TRAINING: A FORECAST

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PROSPECTS FOR LOW-COST ADVANCED COMPUTER-BASED TRAINING: A FORECAST

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FOREWORD

This research and development was conducted in response to Navy Decision Coordinating Paper, Education and Training Development (NDCP-Z0108-PN) under subproject PN.32, Advanced Computer-Based Systems for Instructional Dialogues, and the sponsorship of the Deputy Chief of Naval Operations (OP-01). The objective of the subproject is to develop and evaluate advanced techniques of individualized instruction. This study addresses the impact that the computer hardware revolution will have on the feasibility and costs of advanced computer-based training.

The results of this study are intended for use by the Chief of Naval Operations (OP-01) in policy formulation and planning of future training systems.

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DONALD F. PARKER
Commanding Officer

SUMMARY

Problem

The Navy is developing new computer-assisted instruction (CAI) systems for operational implementation sometime after 1983. To make optimal use of the technological opportunities arising from future hardware, an assessment and forecast of the capabilities and prices of computers over the next 10 years is required.

Objective

The objective of this report is to describe the technological opportunities for intelligent CAI (ICAI) that are expected from new developments in software and hardware technology.

Approach

The recent advances in software for intelligent CAI are reviewed, followed by a discussion of the advantages and disadvantages of trying to implement ICAI on time-sharing computers, personal computers, and LISP machines. (LISP is a symbol manipulation programming language used in artificial intelligence applications.) The prices of the component parts of a LISP machine are projected over a 10-year period, using trends that have been in effect in microelectronics for the last decade.

Results and Conclusions

In 1983 personal stand-alone LISP machines could sell for less than $10,000 and be capable of supporting the most complex ICAI programs. Such machines could become widely available on ships and shore installations. The costs of new CAI systems will be concentrated in the software development phases, while operational implementation for 120,000 men throughout the Navy's schools, ships, and shore installations could be readily accomplished on a budget of less than four million dollars a year. There is need to develop criteria or guidelines for cost effective application of advanced computer-based instruction. Hardware costs will become a minor cost factor in the life cycle costs of such applications.

Five application areas have been identified for which intelligent CAI could be effectively used to maintain and enhance the skills of operating personnel; namely, steam-plant casualty control, antiair warfare tactics, antisubmarine warfare tactics, electronics maintenance, and electronics warfare operations. Other potential applications include computer programming, hydraulics maintenance, and remedial training in basic skills. Each area may require several subprojects for different equipment types or specific duties. The instructional programs for one particular application require 3 to 4 years of development at about $1.0 million annually. Because of the long lead times required for development, it is important that software development be initiated in a timely manner.

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INTRODUCTION

Problem

The operational readiness of the Navy is severely limited by the difficulty in teaching complex skills and by the lack of opportunity to practice them. Examples of such critical problem areas are propulsion engineering casualty control, tactical decision making, electronic warfare operations, and the maintenance of complex hydraulic or electronic equipment. A potential solution is to use computers to provide training and supervised practice of complex skills in simulated environments, so as to produce better trained personnel at lower costs than alternative training methods could provide. Recent developments in computer hardware, computer software, and cognitive psychology offer the opportunity to deliver a new form of computer-based instruction (CBI) to personnel at sea as well as ashore.

There is a danger that this opportunity could be missed without adequate foresight and planning. The Navy is currently conducting R&D on new computer-assisted instruction (CAI) systems that will be ready for operational implementation sometime after 1983. Therefore, it is important that current work be directed to take advantage of the technological opportunities arising from advances in computer hardware and software.

Objective

The purpose of this report is to document the characteristics of the computer hardware revolution that will permit new forms of CBI and to make technological forecasts concerning the possibilities and costs of operational implementation of advanced intelligent computer-based instruction in the Navy after 1983.

Background

In recent years, a new kind of computer-based instruction has been under development, called "intelligent computer-assisted instruction" (ICAI). ICAI uses the tools of artificial intelligence to make the computer more flexible and more like a human tutor in its interactions with the student. In ICAI, the computer is programmed with a symbolic model of the subject matter that enables it to generate information, exercises, and answers to the students' questions by computation and deductive inference.

Some ICAI systems contain a simulation model that operates in conjunction with the tutorial program to create what is known as a "reactive learning environment" (Brown, Burton, & Bell, 1975). The simulator enables the student to carry out exercises in a complex environment that simulates relevant features of real-world problems. The tutorial program guides the student by selecting exercises of graded difficulty, providing hints, criticizing his mistakes, and answering his questions.

ICAI appears to be most useful in training people in complex problem-solving skills, such as electronic troubleshooting, computer programming, algebraic manipulation, tactical decision making, and steam-plant casualty control.

For example, the steam plant reactive learning environment presently envisioned would be based on a computer simulation of the steam plant. The target student populations are Engineering Officer Of the Watch (EOOW) trainees or senior enlisted watch standers. Students would sit in front of a set of three cathode-ray tubes (CRTs) driven by the desk-top stand-alone computer. One CRT would present a set of dynamically selected instrument readings. The second would be a graphics interface to present system diagrams, system-generated graphs, or various diagrams to facilitate explanation of the activities of the steam plant. The third would be the primary tutor or coach interface, presenting dynamically generated "menus" of instructional alternatives, textual material, questions, and answers to guide the student through his interactions with the machine. In a typical session, the student would use the simulator to practice EOOW actions during a casualty or evolution (e.g., lighting off the steam plant). Orders would be given by selecting menu items and/or typing parameters or commands. The casualty or evolution could be selected by the student or the machine tutor, based on its model of the student. The "coach" could stop the simulation to provide student instruction. The session could be reviewed by the student or restarted at a specific point to allow the student to explore alternative actions. The student could ask for explanations of plant behavior, descriptions of correct procedures, or characteristics of plant components.

REVIEW OF CAI DELIVERY SYSTEMS

Time-sharing Systems

In the past, computer-assisted instructional systems have been implemented almost entirely on time-sharing computers. A number of students share a common central processor by using terminals connected to the computer over telephone lines. The terminals range from simple teletypewriters to sophisticated graphics terminals with light pens or touch-panel inputs. Typical graphic terminals cost about $5000.

Time-sharing had several advantages in the past. Computers were expensive, but were much faster than required by any one person. Therefore, several people could share one central processor economically. More parts of the computer could be used at the same time, since one person might be doing computations while another was performing input-output operations. Most time-sharing computers had resources, such as large memories, that a user could occasionally utilize even though his average requirements were small.

Time-sharing systems also have several disadvantages. First, the response time depends on the number of users and the nature of their demands. A single user requiring large amounts of memory and/or disk access can severely affect the response times experienced by all of the others. Second, time-sharing systems generally require large capital investments ranging from $100,000 to several million dollars. Third, the failure of the central processing unit will cause all users to suffer interruption of their work, often accompanied by loss of recently input data.

Personal Computers

Recent development work in CAI has been using stand-alone microprocessor-based personal computers. A typical such system, based on the LSI-11 microprocessor, consists of a 320 x 240 bit-map graphics terminal with keyboard, 56K bytes of memory, and a flexible disk drive for random access of 512K bytes. Figure 1 illustrates a typical personal computer. In 1977 this system sold for $5500 with discounts for large quantities.

Personal computers have several advantages. First, they are almost as cheap as time-sharing terminals; they can be operated at less than one dollar per hour of instruction (Bowles, 1978). They do not require large investments initially; they can be purchased in small increments as need develops. Failure of one unit does not cause interruption in service for more than one person, and the unit is easily replaced with a back-up unit. The systems are small and highly portable, thus facilitating use in remote locations with limited space--such as on board a ship. Security of files is much easier to maintain than in a time-sharing system where dozens of users may be connected to the computer at the same time. Perhaps most importantly, personal computers deliver very fast responses for most problems independently of other users, time of day, or similar factors.

Currently, most personal computers are limited in memory and secondary storage. Their processors are limited to 16-bit addresses and therefore the programs and data arrays cannot exceed 64K bytes. These restrictions will

Figure 1. A personal computer (circa 1977).
The central processing unit, memory, and diskette drive are all contained in the unit on the right.

disappear by mid-1979 when a new generation of 16-bit microprocessors with 32-bit registers and extended addressing capabilities become available in large quantities.

LISP Machines

Perhaps the ultimate personal computer might be a kind of "LISP Machine," now in the prototype stage of development at the Massachusetts Institute of Technology (MIT) (Bowden, Greenblat, Holloway, Knight, Moon, & Weinreb, 1977), Xerox (Moore, 1976), and Bolt, Beranek, and Newman (Ash, Bobrow, Grignetti, & Hartley, 1977).

LISP is a symbol manipulation programming language used in artificial intelligence (AI) applications. Until recently, it has been useful only in the context of time-sharing computers that provide large amounts of memory and disk storage for the complex programs that AI systems require. AI researchers began to find, however, that only a few of their programs could be run on a time-sharing computer simultaneously. In fact, some programs became so complex that they could not easily fit into the memory of a dedicated PDP-10 computer. In order to make further advances in AI, it became necessary to design a special-purpose computer, dedicated to one user at a time, that would handle extremely large LISP programs efficiently.

It is projected that LISP machines can be built at a fraction of the cost of time-sharing computers. The parts cost for the MIT machine is about $32,000. Such a machine would sell commercially for two to four times the parts cost in order to cover labor, marketing, and software. Other LISP machines now under development may be manufactured in 1980 at a parts cost as low as $10,000.

A minimal configuration for a LISP machine would have 512K bytes of main memory, 50 megabytes of disk or secondary storage, 24-bit or larger direct addresses, a graphics terminal, a hardware paging mechanism, and several thousand bytes of user modifiable control store. By microprogramming certain common LISP functions, execution speed can be increased while program storage requirements can be decreased over conventional computers.

A LISP machine is not necessarily a special piece of hardware. It could be a general-purpose computer that is user-microprogrammable, and that has a large address space and paging hardware. For example, it has been suggested that a PRIME 400 or 450 computer could be microprogrammed to function as a LISP machine. The PRIME 400 has been in production since 1976. A suitably configured machine was priced at about $80,000 in 1978. The PRIME 450 will be available in 1979 for about $45,000 in original equipment manufacturer (OEM) quantities. The costs of developing microcode and LISP software would run about $160,000, but this expense would be incurred only once.

It should be realized that what is referred to here as a "LISP Machine" is actually a general symbolic processor that is well suited to symbolic, nonnumeric processes and languages. It is not necessary that most users of LISP machines be able to program in LISP, or understand the complex systems they interact with. LISP machines will be much easier for the average person to use than conventional computers, because they will be able to react intelligently to the user's requests, correcting his minor spelling and punctuation

errors, allowing him to undo calculations when he changes his mind, and presenting on-line help in reply to questions phrased in ordinary English. For this reason, LISP machines are likely to be widely used in automated office systems, military command and control systems, educational systems, and other applications where man-machine interfaces are especially important.

LISP machines are essential for the practical use of ICAI. Up to now, intelligent computer-based training has been developed almost entirely on large time-sharing computers, with all of the disadvantages previously described. Probably the only acceptable delivery system for most ICAI will be individual LISP machines that can accommodate one student at a time.

The minimal LISP machine described here could be the basis for a family of computers specialized for different purposes. For use in CAI, a variety of input-output devices could be interfaced to the computer: touch panels, writing tablets, video disk, voice output, voice input, and even simulated equipment control panels. For research in artificial intelligence, some models may be equipped with increased amounts of memory and disk storage and may be interfaced with robot arms, remote vehicles, and video cameras. Since the minimal LISP machine described here should suffice for many CAI applications, however, the remainder of this paper assumes an unaugmented basic configuration.

FORECAST

The question now arises as to how soon economically feasible ICAI will appear. Ignoring software development costs for the time being, the main barrier to widespread use of ICAI has been hardware cost. Ten dollars per hour on a time-sharing computer or $80,000 for a personal LISP machine for each student are prices that cannot be justified except in very special applications.

To project the prices of LISP machines 5 years from now (i.e., 1983), several basic relationships should be noted. As shown in Figure 2, the number of logical functions incorporated in a single LSI chip has doubled every year since 1959, and the trend is expected to continue for at least another decade (Noyce, 1977a). The chip cost per logical function, shown in Figures 3 and 4, has tended to decline about 25 percent per year, except for random access memories (RAMs) (Figure 5), which decline 35 percent yearly in price (Noyce 1977b).

Current RAM chips hold 16K bits. If densities quadruple every 2 years, then by 1982, three chips will hold 256K bits. Thus, a 512K byte memory will require 16 chips as compared with today's 32 chips for a 64K byte RAM. Table 1 shows the current and projected memory component costs.

The projection shows that a 512K byte memory could be built in 1983 at about the same price as a 64K byte memory could be built today. Only half as many chips would be needed, thus reducing physical size and the number of interconnections. Thus, the memory of a 1983 LISP machine will be comparable in price to that of a personal computer in 1978.

The cost of the CPU chip for a 1983 LISP machine can be considered negligible. The recently announced Zilog 8000 microprocessor is nearly complex enough to serve as the basis for a LISP machine. What is still lacking is a user-modifiable control store and 32-bit wide logic throughout. Such a chip will almost certainly appear within 4 years and sell for less than $200 to original equipment manufacturers and less than $1000 to end-users.

These estimates are somewhat more conservative than others in the literature. For example, Siewiorek, Thomas, and Scharfetter (1978) project a 512K-bit RAM in 1983 and a 200K gate circuit on a single chip costing $100. They say that "a three-chip, 24-processor, 2.5-3.5 MIPS (million instructions per second) modular multi-microprocessor with three-quarters of a million words of 18-bit memory could be built out of 1983 technology." Dhaka (1978) believes that "by the mid-eighties, a 32-bit microcomputer with one million bits of memory could be made on a single silicon chip for a cost of about $20."

The costs of secondary memory are declining about 25 percent per year, as shown in Figure 6. About 50 megabytes of such secondary storage are needed for a LISP machine. In July 1978, one manufacturer advertised a 50 megabyte removable disk drive at $21,800 with a controller. Assuming a 25 percent decline in price annually, the 1983 projected price would be $5173. This is a conservative forecast, since recently-developed nonremovable "Winchester" disks may satisfy requirements at less than $5000 by 1980 (Morgan, 1978).

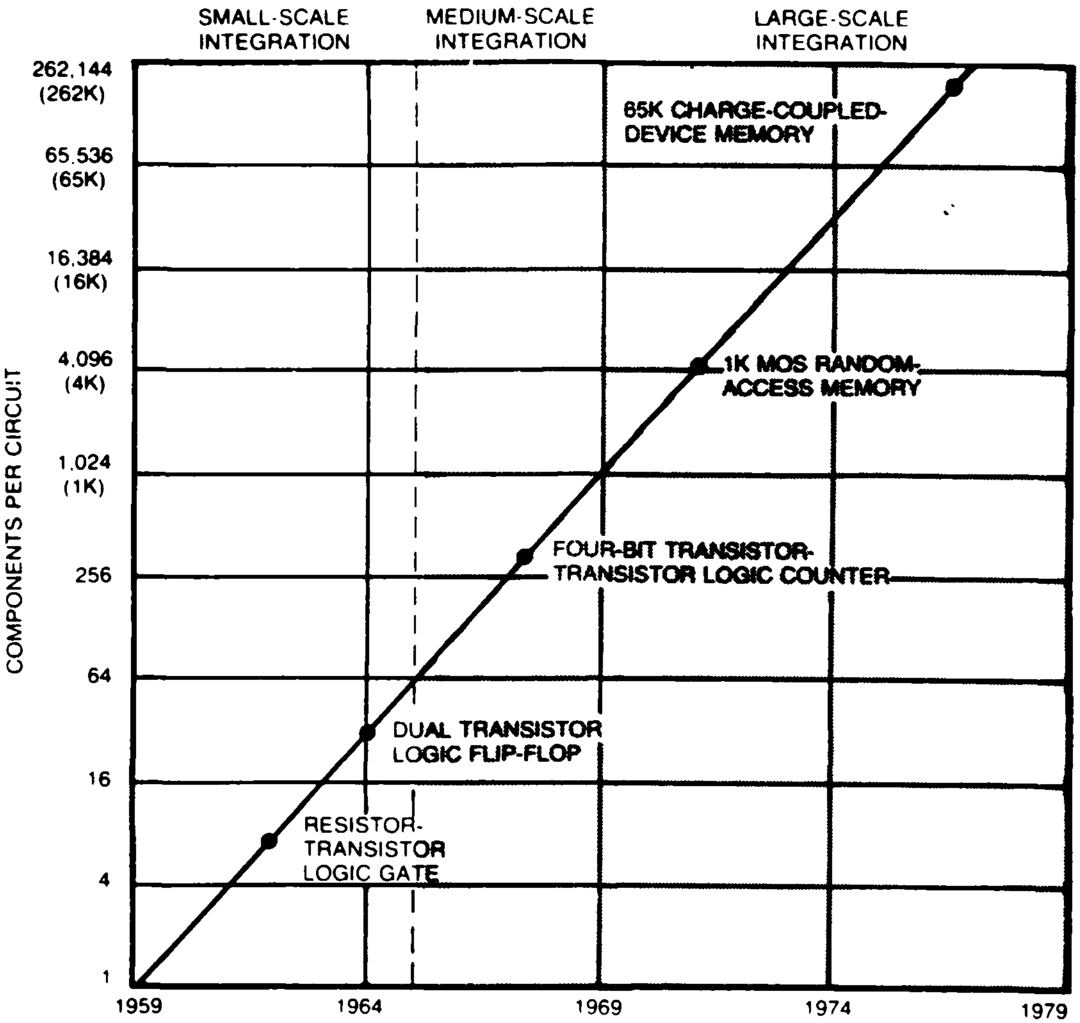

Figure 2. Number of components per circuit in the most advanced integrated circuits has doubled every year since 1959, when the planar transistor was developed. Gordon E. Moore, then at Fairchild Semiconductor, noted the trend in 1964 and predicted that it would continue.

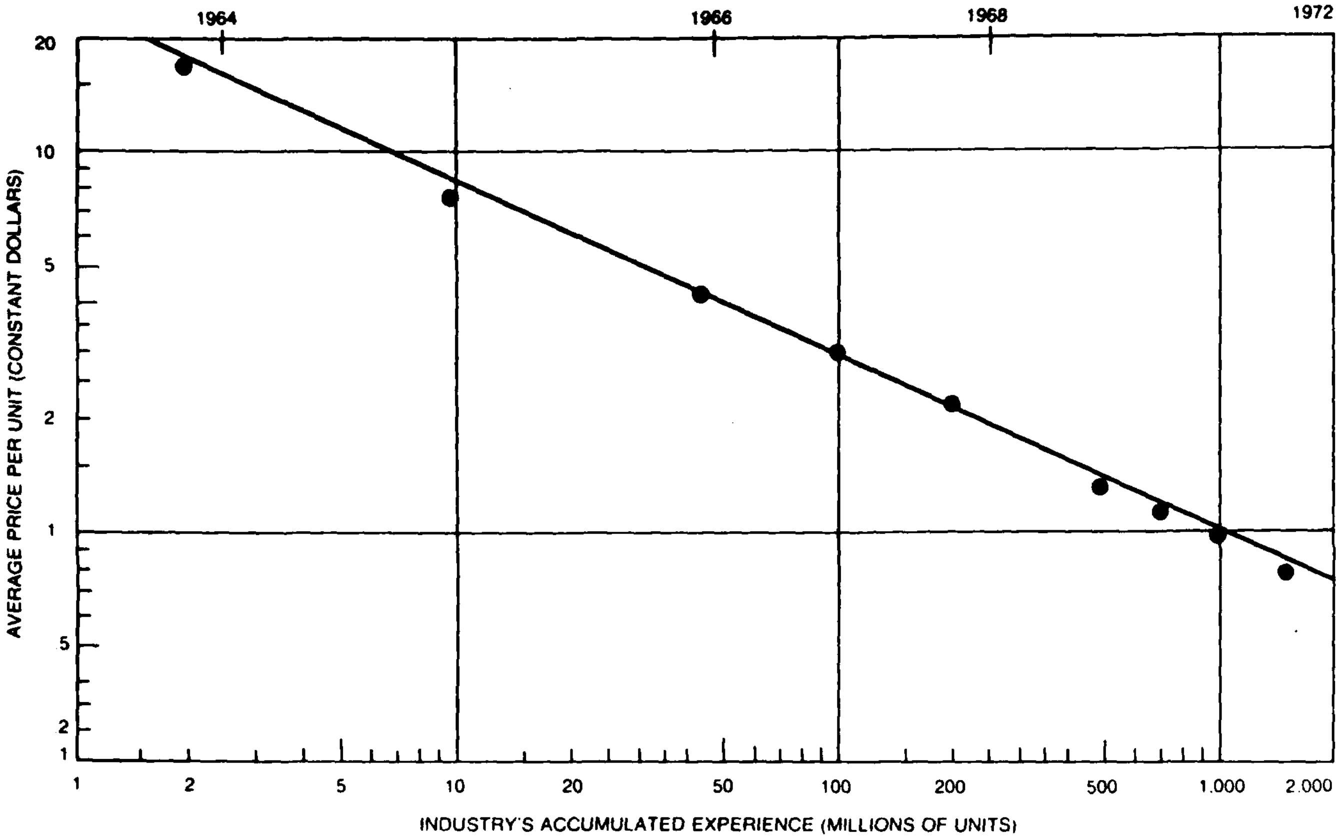

Figure 3. Prices of integrated circuits have conformed to an experience curve common to many industries, declining about 28 percent with each doubling of the industry's cumulative experience (as measured by the number of units produced). It is the particularly rapid growth of the microelectronics industry that has made the rate of decline in prices appear to be higher than the rate in other industries.

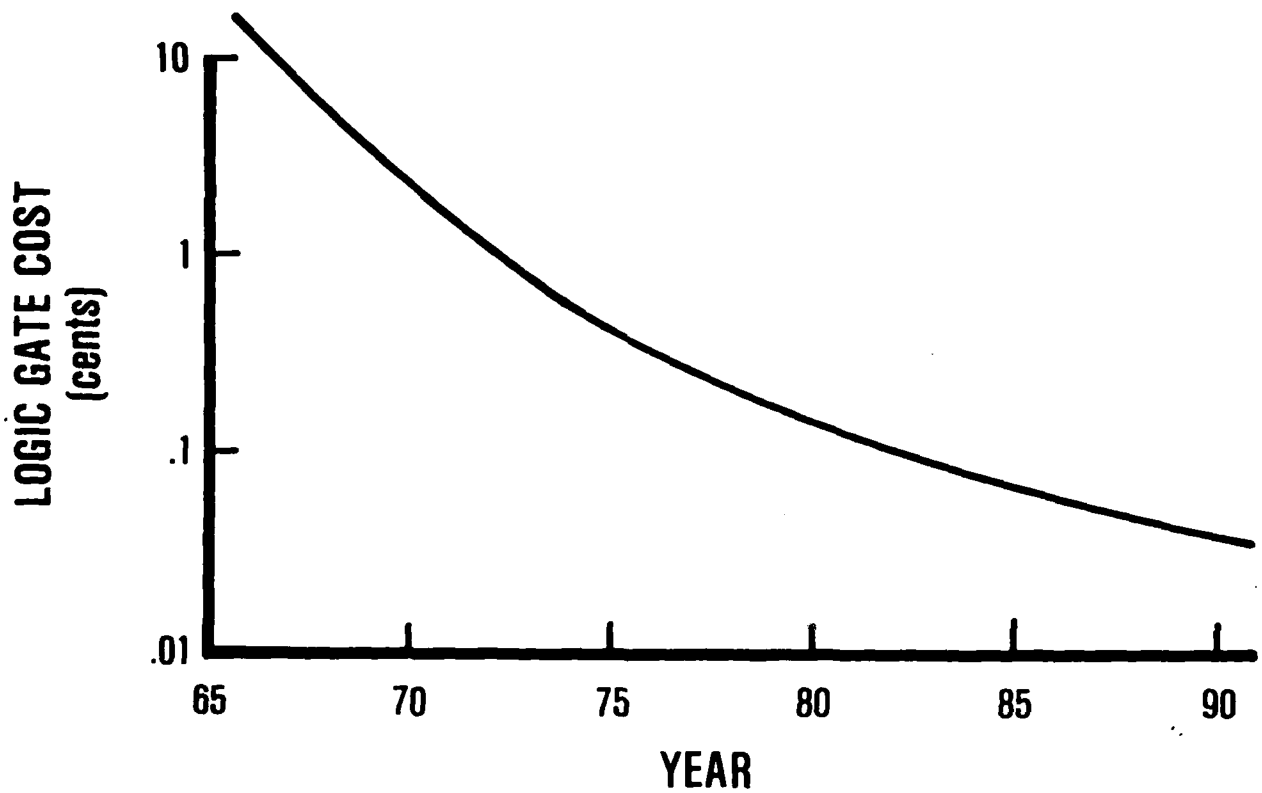

Figure 4. Cost of logic arrays versus time.

From "Large-Scale Integration: What is Yet to Come?" by R.N. Noyce. Science, Vol. 195. Copyright 19xx 18 March 1977 by the American Association for the Advancement of Science.

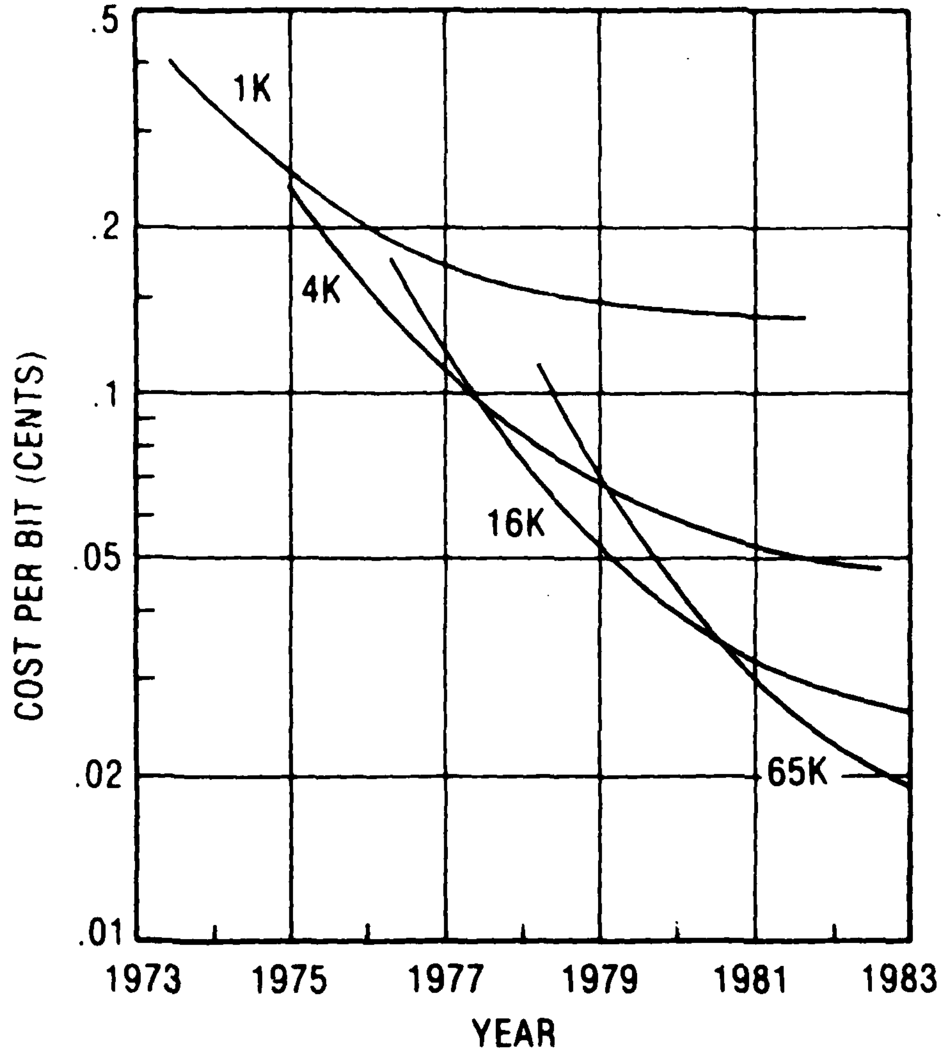

Figure 5. Cost per bit of computer memory has declined and should continue to decline as shown here for successive generations of random-access memory circuits capable of handling from 1,024(1K) to 65,536(65K) bits of memory. Increasing complexity of successive circuits is primarily responsible for cost reduction, but less complex circuits also continue to decline in cost.

Table 1

Present and Projected Memory Component Costs and Capacities

Component	1978	1983
Memory size	64K bytes	512K bytes
Chip size	16K bits	256K bits
Chips	32	16
Cost/chip	$16	$30
Chip cost	$512	$480
End-user price	$2202	$2064

Magnetic bubble memories will not replace the 50-megabyte disk by 1983. Solid-state direct-access devices, such as bubble and charge-coupled devices (CCD), are expected to replace flexible disks and fixed-head disks for small amounts of secondary storage (less than one megabyte) in the near future. At any given moment in time, the costs of solid-state devices vary directly with their storage capacities, while disks vary as the square roots of their capacities, and have an overhead cost even with minimal capacity. Hence, disks will retain a cost advantage for quantities of storage greater than 30 megabytes until at least 1990. The main impact of solid-state devices will be to close the gap in access times between main memory and disk storage (Figure 7) with the result that effective retrieval from secondary storage will appear to be several times faster. An estimate can now be made of the total end-user price of a LISP machine in 1983, as shown in Table 2.

Projected prices for the components of a LISP machine from 1978 to 1990 are presented in Figure 8. Some of the lines of the graph deserve comment. The cost line for color displays differs from the other components of Figure 8 in that the display is assumed to be a constant budget item whose capabilities may increase over time. The line for the central processing unit (CPU) is a continuous approximation to discontinuous price changes. A shift in the manner of design and construction of CPUs is precipitating a quantum drop in CPU costs for a LISP machine during the next 5 years.

One should realize that these projections represent technological opportunities rather than actual predictions. There is no reason to believe that a new LISP machine will be designed and built with the latest electronic components in any given year. Typically, a computer is manufactured and sold for a 5-year period with only minor changes in design and pricing. Price changes tend to be discontinuous, rather than continuous as Figure 8 implies, and they reflect market conditions as much as manufacturing costs. The conclusion of this forecast is that the potential will exist for LISP machines costing under $10,000 as early as 1983.

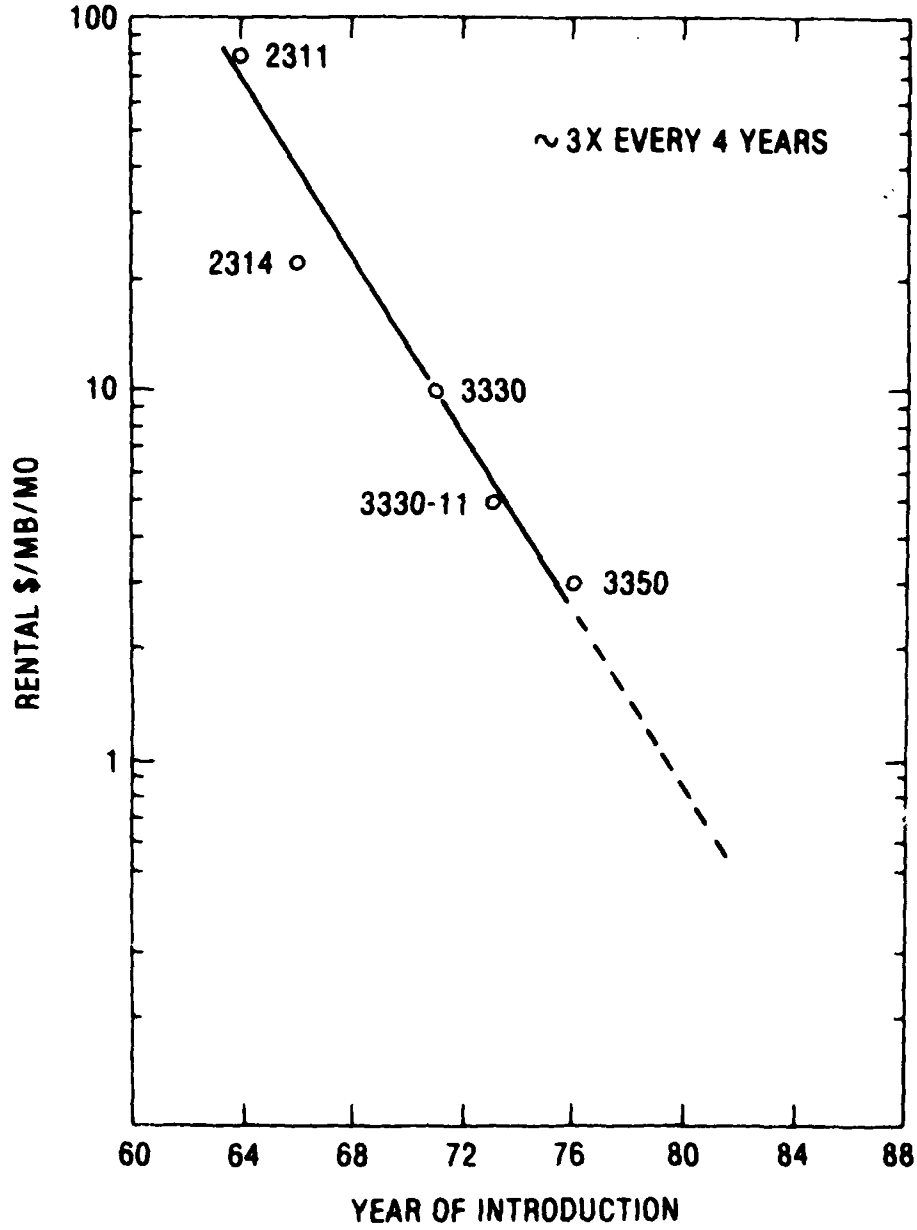

Figure 6. The steep and steady decline in the cost of direct-access storage suggests that this technology, at least, faces no immediate barriers.

From "Basic Technology" by H.L. Caswell et al. Computer, September 1978. Copyright by the IEEE Computer Society.

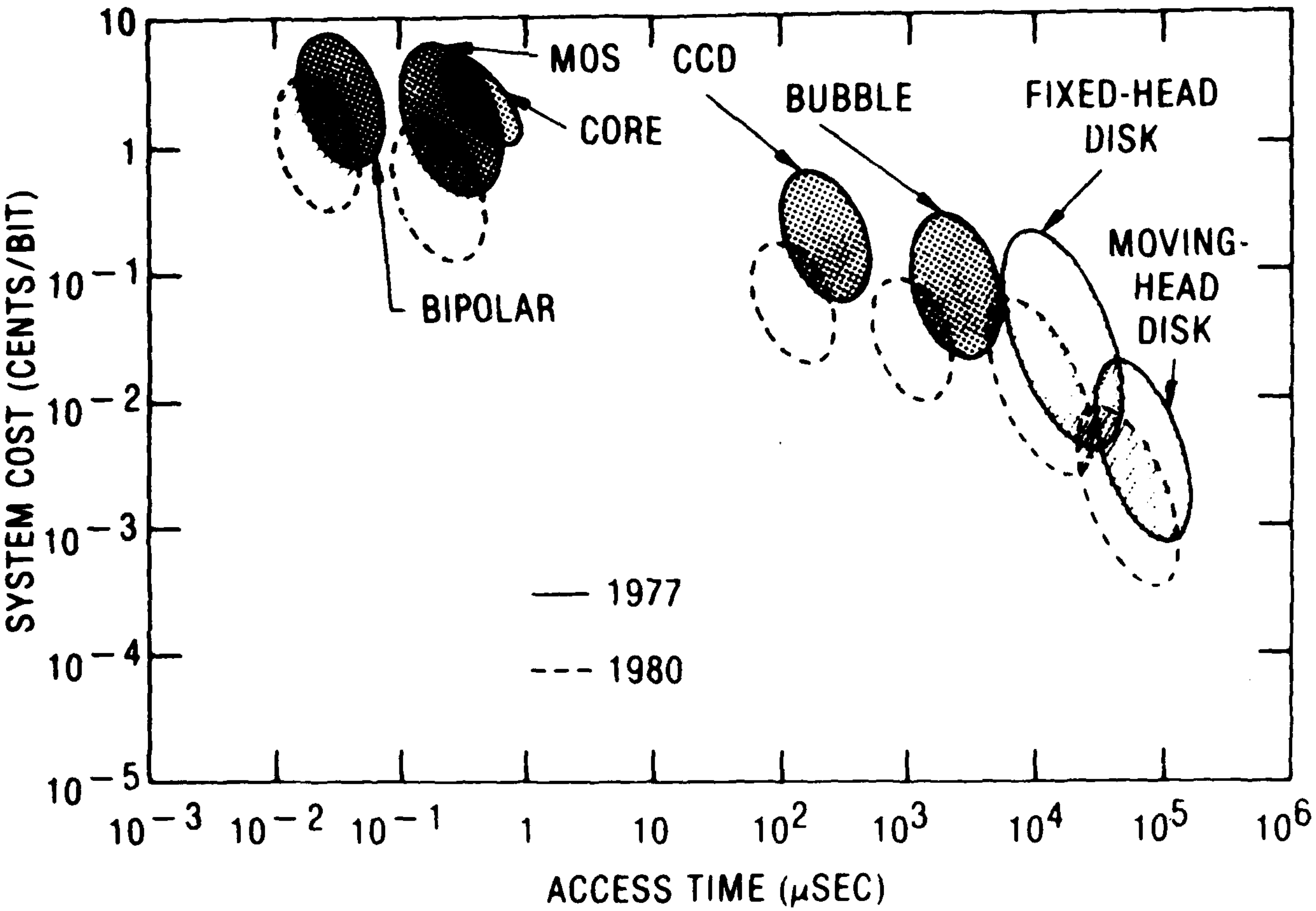

Figure 7. The gap in access times between main memory and disk storage is likely to be filled by the greater use of bubble and charge-coupled devices.

From "Basic Technology" by H.L. Caswell et al. Computer, September 1978. Copyright by the IEEE Computer Society.

Table 2

Price Breakdown of 1983 LISP Machines

Component	Cost
CPU	1000
Memory (512K bytes)	2064
Disk (50 Mbytes)	5173
Keyboard	220
Color Display	1000
Total	9457

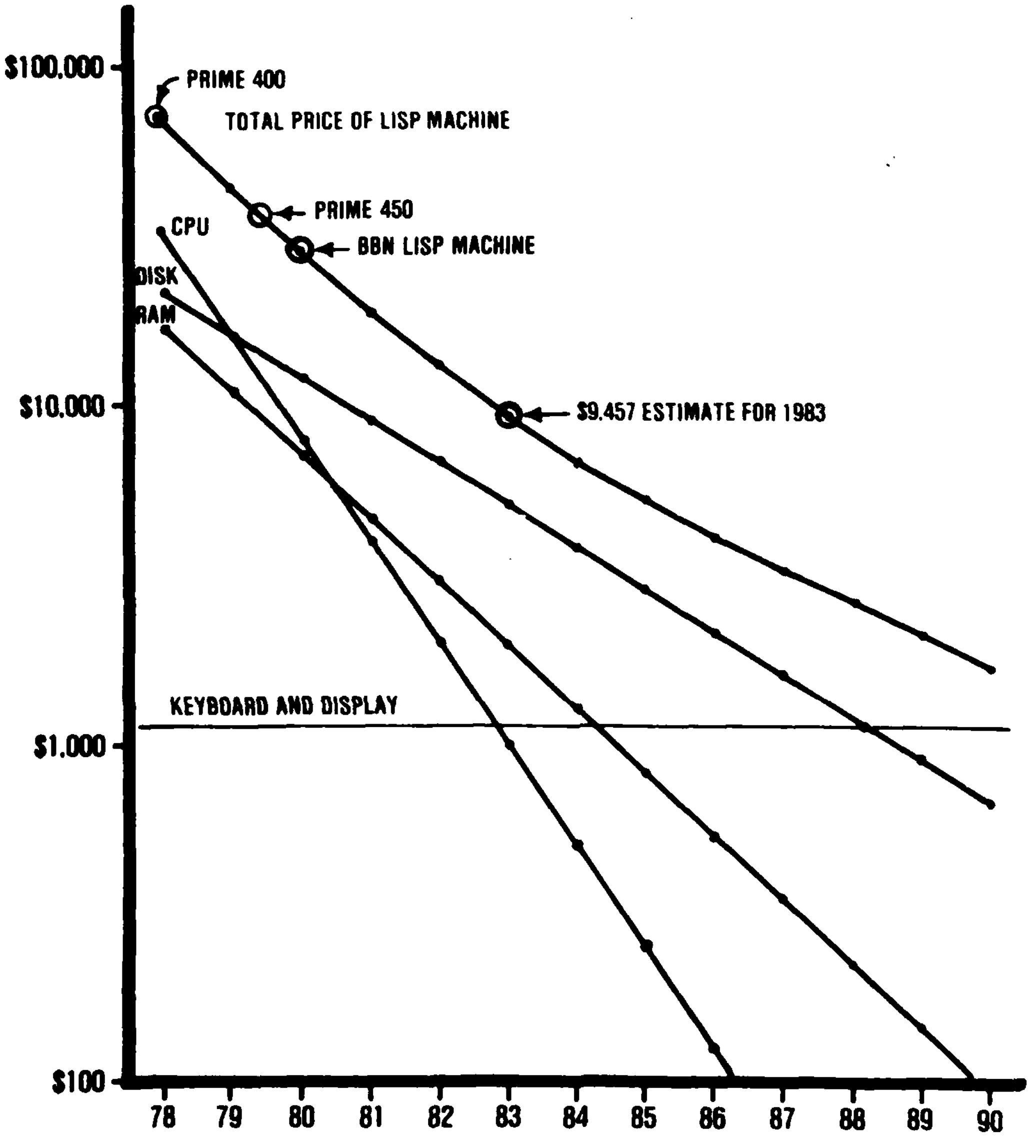

Figure 8. Prices of lisp machine components projected from 1978 to 1990.

DISCUSSION

Let us consider what might be the upper limits of the number of LISP machines the Navy could use for intelligent computer-based training. The following is one scenario for the application of ICAI to an array of Navy training and skill maintenance functions. Although the decision to extend ICAI from an initial pilot program or a critical training requirement to others would depend upon validation results and cost/effectiveness analyses for additional applications, this scenario reveals that the extension of ICAI to a number of applications is economically feasible, especially with an incrementally phased acquisition program. The R&D software (exercise or lesson program) costs dominate the cost analysis. The principal message from this forecast is that the Navy should not wait until ICAI delivery hardware is available at tolerable costs. Rather, a pilot development and demonstration program should be initiated in parallel with a cost/effectiveness analysis of a number of options for expansion of the ICAI capability.

About 1700 LISP machines would be needed to provide on-board practice and tutoring in steam-plant casualty-control for 397 major fighting ships in the Navy. Another 200 machines might be needed for tactical decision-making exercises. Other applications such as electronics warfare operations, electronics trouble-shooting, hydraulics maintenance, and remedial training in basic skills might bring the total Navy requirement up to 4000 LISP machines. A minimum of two machines per ship is necessary for reliability purposes; once the LISP machines are in place, however, they could be shared among several Navy applications, since the same computer is capable of running a variety of instructional programs and exercises.

The total Navy operating force that might ultimately benefit from ICAI consists of approximately 20,000 unrestricted line officers and 100,000 petty officers in the following technical ratings:

- Boiler Technician (BT).
- Data Processing Technician (DP).
- Electrician's Mate (EM).
- Engineman (EN).
- Electronics Technician (ET).
- Electronics Warfare Technician (EW).
- Fire Control Technician (FT).
- Interior Communications Technician (IC).
- Machinist's Mate (MM).
- Operations Specialist (OS).
- Radioman (RM).
- Sonar Technician (ST).

Assuming that 1 hour per week would suffice for the purpose of maintaining and enhancing skills and that each machine can be used 60 hours per week, 2000 LISP machines would suffice to meet this demand. It would appear, however, that about 4000 LISP machines would be a safe upper limit for Navy requirements. This would resolve scheduling conflicts, permit distribution to small ships, and allow for downtime.

Table 3 shows one possible procurement plan for LISP machines phased over a 10-year period, with the total number of machines doubling every year for the first 6 years. The conservative assumption is made that prices will not decline after 1988, but will level off to $3,000 per machine. Maintenance costs are assumed to be 10 percent of the initial purchase price, and equipment is replaced after 5 years. The program levels off to $3.6 million a year for a constant inventory of 4000 LISP machines. These figures can be compared with the Navy's total budget of more than one billion dollars a year for special skill training, not including Fleet exercises and on-the-job training. As another comparison, a single training device such as the Navy Electronics Warfare Training Simulator presently costs over $30 million.

Table 3

Sample Navy Acquisition Plan for LISP Machines

Date	Unit Price $	Number Purchased	Maintenance $000	Total Inventory	Total Cost $000
1983	9457	50	47	50	520
1984	6929	50	82	100	428
1985	5244	100	134	200	659
1986	4088	200	216	400	1034
1987	3322	400	349	800	1678
1988	3000	800	542	1550	2942
1989	3000	800	747	2300	3147
1990	3000	800	935	3000	3335
1991	3000	800	1093	3600	3493
1992	3000	800	1200	4000	3600

At first, the market for LISP machines may be less than 4,000 because of the time and difficulty of developing software. The first ICAI systems developed will be more costly and require greater lead times than follow-on efforts. Initial systems will probably take 4 to 5 years at a cost of about $1.0 million per year. Constraints on software development and the iterative nature of the development of these systems preclude the acceleration of projects by greater funds or manpower. Follow-on systems will use varying amounts of the software and technology developed in early efforts. As a result, they will probably require from 1 to 3 years of development at costs of from $0.5 to $1.0 million per year.

The software and lesson development costs will be considerably larger than the hardware implementation costs. About five major ICAI projects, each with an annual budget of $1.0 million, would cost about $5.0 million a year. Thus,

the software costs associated with Table 3 could run as high as $25 million to develop five major applications. The total 10-year cost would be $21 million for hardware and $25 million for software. Assuming each LISP machine is used 30 hours per week, the total number of hours of instruction delivered over a 10-year period will be 25 million, so that the cost per student-hour is only $1.83.

Finally, it should be emphasized that these projections refer only to the computers needed to support ICAI, which is only one kind of computer-based instruction. Many Navy schools and training programs could benefit from more conventional computer-assisted instruction, training simulators, and computer-managed instruction implemented on personal computers. Such computers do not necessarily have to be LISP machines, although LISP machines offer many advantages in facilitating man-machine interaction for such training. In any case, the eventual Navy "market" for personal computers could be much larger than the numbers projected in this report.

CONCLUSIONS

In 1983, personal stand-alone LISP machines could sell for less than $10,000 and be capable of supporting the most complex ICAI programs. Such machines will become widely available on ships and shore installations. The costs of new CAI systems will be concentrated in the software development phases, while operational implementation for 120,000 men throughout the Navy's schools, ships, and shore installations could be readily accomplished on a budget of less than four million dollars a year.

Five application areas have been identified for which intelligent CAI could be effectively used to maintain and enhance the skills of operating personnel; namely, steam-plant casualty control, antiair warfare tactics, antisubmarine warfare tactics, electronics maintenance, and electronics warfare operations. Other potential applications include computer programming, hydraulics maintenance, and remedial training in basic skills. Each area may require several subprojects for different equipment types or specific duties. The instructional programs for one particular application require 3 to 4 years of development at about $1.0 million annually. Because of the long lead times required for development, it is important that software development be initiated in a timely manner.

A reasonable final level of R&D funding might be about $5.0 million annually, more than the hardware cost of operational implementation throughout the Navy. This situation runs contrary to the usual budgeting policy that tends to allocate R&D funds as a small percentage of operations costs. Present Navy advanced development for ICAI (not including basic research and exploratory development) is budgeted at about $500,000 during FY79, about 10 times smaller than the level suggested in this report. As a result, when the $10,000 personal LISP machine appears on the market, only a few of its potential training applications will be ready for Navy use.

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